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Regional Relationships between Geomorphic/Hydrologic Parameters and
Surface Water Chemistry Relative to Acidic Deposition

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REGIONAL RELATIONSHIPS BETWEEN GEOMORPHIC/ HYDROLOGIC PARAMETERS AND SURFACE WATER CHEMISTRY RELATIVE TO ACIDIC DEPOSITION

BARRY P. ROCHELLE¹, CHARLES I. LIFF², WILLIAM G. CAMPBELL¹,
DAVID L. CASSELL¹, M. ROBBINS CHURCH^{3*} and RICK A. NUSZ⁴

¹NSI Technology Services Inc., 300 S.W. 35th Street, Corvallis, OR 97333 (U.S.A.)

²Utah State University, 300 S.W. 35th Street, Corvallis, OR 97333 (U.S.A.)

³U.S. Environmental Protection Agency, 300 S.W. 35th Street, Corvallis, OR 97333 (U.S.A.)

⁴FTN Associates, 3 Innwood Circle, Suite 200, Little Rock, AR 72211 (U.S.A.)

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ABSTRACT

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We determined geomorphic and hydrologic parameters for 144 forested, lake watersheds in the Northeast (NE) of the United States based primarily on measurements from topographic maps. These parameters were used to test for relationships with selected surface water chemistry relevant to acidic deposition. Analyses were conducted on regional and subregional scales delineated based on soils, land use, physiography, total sulfur deposition and statistical clustering of selected geomorphic/hydrologic parameters. Significant relationships were found among the geomorphic/hydrologic parameters and the surface water chemistry for the NE. Elevation had the most significant relationship with surface water chemistry, particularly in the mountainous areas of the NE. Other factors occurring consistently as significant predictors of surface water chemistry were maximum relief, relief ratio, runoff, and estimates of basin elongation. Results suggest that elevational parameters might be surrogates for other watershed characteristics, such as soils or spatial deposition patterns. Stream order was a significant class variable with lower order systems tending to be associated with low pH and acid neutralizing capacity high sulfate and total aluminum. Analysis at the sub-regional level improved the correlations among the descriptive parameters and surface water chemistry over the findings for the total NE. This improvement in correlation is probably due to reduced heterogeneity within the data at the sub-regional level. Also, stratifying the data based on factors such as soils and sulfur deposition removes some of the influence these factors have on surface water chemistry.

INTRODUCTION

Hydrologic processes have been identified and discussed as important factors affecting the response of surface waters to acidic deposition (Chen et

* Corresponding author.

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Fig. 1. Location of the 144 Northeast study sites.

al., 1984; Peters and Driscoll, 1987). The flowpaths followed by water moving through the terrestrial portion of a watershed are important in controlling the chemistry of surface waters at risk to acidification (Chen et al., 1984; Newton and April, 1982). Acidic deposition that rapidly moves through the watershed system will have limited contact with the soil resulting in reduced potential for neutralization.

Categorizing watershed hydrologic response is an important step in identifying the potential for neutralization. Hydrologically "quick" (flashy) response systems have a greater proportion of the total runoff in the form of quick flow (e.g., surface runoff, subsurface stormflow) resulting in a limited contact system (Peters and Driscoll, 1987). Conversely, a hydrologically "slow" response system will be dominated by baseflow (groundwater) and potentially have greater contact with the soil substrate.

A significant amount of work has attempted to relate hydrologic characteristics with mapped geomorphic parameters for forested watersheds (Carlston, 1963; Lull and Sopper, 1966; Hewlett and Hibbert, 1967; Woodruff and Hewlett, 1970; Vorst and Bell, 1977; Dingman, 1981). Past work specifically looking at acidic deposition and watershed characteristics by Johnson et al. (1981) found distinct relationships between surface water chemistry and elevation and stream order for the Hubbard Brook watershed in New Hampshire. In general, most previously reported research is at the "event" (i.e., snowmelt, rainstorm)

level or covers short time periods (i.e., days or weeks). In this study we use an "index" chemistry value determined in the U.S. Environmental Protection Agency's (EPA) National Surface Water Survey (NSWS) (Linthurst et al., 1986; Landers et al., 1988). Therefore, hydrologic response as discussed here is at an annual scale.

In this study we test for apparent relationships among mapped watershed hydrologic and geomorphic parameters that might affect (or be related to) hydrologic response and selected surface water chemistry variables for 144 forested watersheds in the Northeast (NE) of the United States (Fig. 1). These surface water chemistry variables are especially relevant to acidic deposition effects. We are testing for correlations among chemistry and watershed factors both on a large regional scale (NE, Fig. 1) and subregional scale as stratified by statistical clustering or geographic factors.

METHODS

Surface water chemistry

Water chemistry data for a 144 lake watershed subset of the U.S. EPA's NSWS Eastern Lake Survey (Linthurst et al., 1986; Landers et al., 1988, Fig. 1) were used. The NSWS collected surface water chemistry for a stratified sample of lakes in the NE for the purpose of estimating population percentage of acidic lakes at an index period (i.e., fall period of complete mixing for these lakes). Runoff and other direct hydrologic measurements were not part of the NSWS sampling design. For this study we have used the index concentrations of SO_4 , acid neutralizing capacity (ANC), pH, sum of base cations (SBC; Ca and Mg only), dissolved organic carbon (DOC), SiO_2 , color and total Al as measures of surface water chemistry. Of particular interest to studies of acidic deposition are SO_4 , ANC, pH and SBC. Detailed discussion of sampling techniques and quality assurance/quality control were presented by Linthurst et al. (1986).

Geomorphic parameters

Geomorphic parameters were defined from map measurements taken from 7.5 minute (1:24,000) topographic maps (when available) or from 15 minute (1:64,000) topographic maps (when 7.5 minute maps were not available) from the U.S. Geological Survey topographic map series. All map information was digitized and entered directly into a computer database via an interactive program. Table 1 describes all measured or computed parameters. The majority of the measures identified in Table 1 were selected from geomorphic/hydrologic parameters listed by USDI (1977). Additionally, we have included parameters that are specifically descriptive of lake watersheds. These were watershed area to lake area ratio (WS-LA), watershed perimeter to lake perimeter ratio (PERIMRAT), and percent area in open water bodies (H_2O -WS) (includes the primary lake of the watershed).

TABLE 1

Mapped and calculated geomorphic parameters

Parameter	Description	Units
<i>Measured</i>		
B-CENT	Drainage basin centroid expressed as an X,Y coordinate	
B-LEN	Length of drainage basin; air-line distance from basin outlet to farthest upper point in basin	km
B-PERIM	The length of the line which defines the surface divide of the drainage basin	km
H ₂ O-AREA	Area of all open water bodies in drainage basin	km ²
INTERMIT	Total length of intermittent streams as defined from USGS topographic maps of aerial photos	km
LAKEAREA	Area of the primary lake	km ²
L-CENT	Primary lake centroid expressed as X,Y coordinates	
L-PERIM	Perimeter of primary basin lake	km
MAX-ELEV	Elevation at approx. highest point	m
MIN-ELEV	Elevation of primary lake	m
PERIN	Total perennial stream length as defined from USGS topographic maps and aerial photos	km
SUB-BAS(n)	Area of each subcatchment in the drainage basin	km ²
STRMORDER	Maximum stream order (Horton) of streams in the watershed (aerial photos used to aid in reducing coding problems between 7.5 and 15 minute maps)	
TOTSTRM	Total stream length; combination of perennial and intermittent	km
WS-AREA	Total watershed area	km ²
<i>Calculated</i>		
B-SHAPE	Basin shape ratio; $(B-LEN)^2/WS-AREA$	
B-WIDTH	Average basin width; $WS-AREA/B-LEN$	km
COMPACT	Compactness Ratio; ratio of perimeter of basin to the perimeter of a circle with equal area; $PERIM/[2(\pi WS-AREA)^{0.5}]$	
DDENSITY	Drainage Density; $TOTSTRM/WS-AREA$	
ELONG	Elongation Ratio; $(4WS-AREA)/L-BEN$	
H ₂ O-WS	Ratio of open water bodies area to total watershed area $H_2O-AREA/WS-AREA$	
MAX-REL	Maximum relief; $MAX-ELEV - MIN-ELEV$	m
M-PATH	Estimate of mean flow path;	m
PER-DD	Drainage density calculated from perennial streams only; $PERIN/WS-AREA$	
PERIMRAT	Ratio of the lake perimeter to the watershed perimeter; $Lake Perimeter/B-PERIM$	
REL-RAT	Relief Ratio; $(MAX-ELEV - MIN-ELEV)/B-LEN$	
ROTUND	Rotundity Ratio; $(B-LEN)^2/(4WS-AREA)$	
WM-PATH	Estimate of weighted mean flow path	m
WS-LA	Ratio of the total watershed area to the area of the primary lake	
<i>Additional</i>		
RT*	Lake retention time	yr
VOL*	Volume of the primary lake	10 ⁶ m ³
RUNOFF	Average annual runoff; interpolated to each site from Krug et al. (1988) runoff map	cm

*Determined as part of US EPA National Surface Water Survey (see Kanciruk et al. (1986) for calculation methods).

Three additional measures included in the geomorphic/hydrologic data base are average annual runoff (RUNOFF), retention time (RT) for the primary lake and lake volume (VOL). RUNOFF was interpolated (Rochelle et al., 1989) from a runoff contour map (Krug et al., 1988) of average annual runoff for 1951-1980. RT and VOL were estimated by the NSWWS (Kanciruk et al., 1986).

Quality assurance

Subjectivity is often associated with mapped measurements. To maximize consistency, all map measurements were made by the same individual. Also, we conducted several other checks to determine an estimate of the precision of our measurements. These were comparing watershed elevation and area measurements against data from an independently constructed database (Lee et al., 1989). Elevation estimates were within 10% between the two database. For 136 of the 144 watersheds, area estimates were within 10%. The remaining eight watersheds were generally small watersheds where small differences resulted in larger percent differences.

A second data quality check involved redigitizing a 10% subset of the watersheds and comparing the results to the original measurements. The percent differences were compared to published measurement errors (USDI, 1977). Large percent differences were checked to determine the cause and corrections were made where necessary.

Stratification

Because regional variability might obscure some relationships, we divided the NE into more homogeneous subregions based on regionalization schemes using geography, geomorphology and soils and also groupings based on statistical clustering on selected hydrologic/geomorphic parameters. An additional stratification scheme used atmospheric deposition of sulfur as a basis for clustering the NE watersheds. Soils, geology and deposition chemistry are factors that probably influence the relationship of the hydrology/geomorphic parameters to surface water chemistry. Defining subregions, either in terms of physical or statistical criteria, might aid in the identification of trends by stratifying the sample prior to statistical analysis. In addition, stratification might remove the major effects of the additional influences discussed above.

We used two geographic/geomorphic classifications to stratify the study watersheds. These two classifications are based strongly on soils and land forms and help remove some of the possible soils and geology influences on surface water chemistry. First, we stratified the study watersheds based on the Major Land Resource Area (MLRA; USDA, 1981) classification system (Fig. 2). MLRA's are defined by a combination of factors — the primary USDA interest is agriculture and hence, soils represent a major component of the classification. Second, geographic/geomorphic stratification is based on Land Surface Forms (LSF; Hammond, 1964). LSF represents an empirical analysis of land

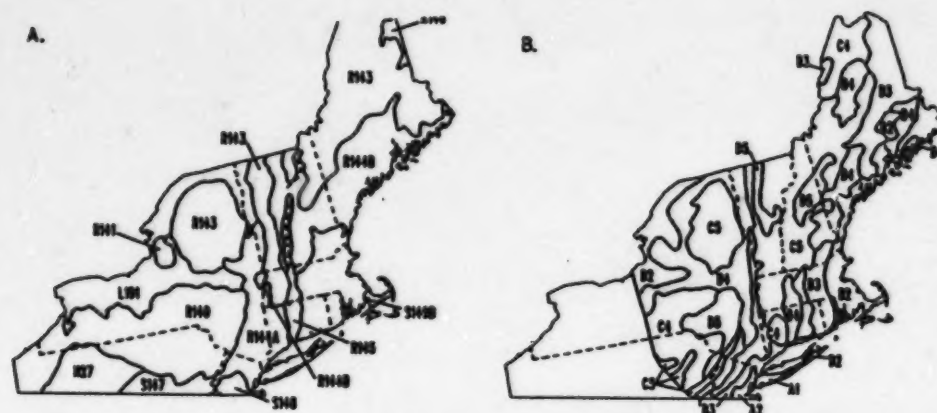


Fig. 2. (A) Major Land Resource Association (MLRA) of the NE (adapted from USDA, 1981); (B) Land Surface Forms (LSF) of the NE (adapted from Hammond, 1969).

surface based on a selected group of surface characteristics including slope, local relief and profile type (Fig. 2).

Statistical clustering was performed using the CLUSTAR program (Romesburg, 1984; Romesburg and Marshall, 1984). The clustering routine uses hydrologic/geomorphic parameters potentially having significant influence on hydrologic response. The attributes are first standardized. The standardization procedure results in removal of the potential effects due to attributes with difference scales. Transformed attributes have a mean of zero, a standard deviation of one and are dimensionless. A resemblance matrix was constructed using the average Euclidean distance coefficient (the distance between two objects in the attribute space divided by the dimension of the attribute space). The objects in the resemblance matrix were clustered using an unweighted pair-group method using arithmetic averages. Dendrograms were constructed based on the clustering. The resemblance and data matrices were then rearranged to reflect the similarities shown in the dendrograms. A small number of classes that were defined were chosen and used as strata in further regression analysis (Table 2).

TABLE 2

Empirical clustering classes for stream order, elevation and relief ratio

Class	STRORDER	ELEV(m)	REL-RAT
1	0 and 1	< 135	< 0.03
2	2	13 ≤ 270	0.03 ≤ 0.04
3	3	270 ≤ 465	0.04 ≤ 0.07
4	4	465 ≤	0.07 ≤ 0.10
5	-	-	0.10 ≤

TABLE 3

Stratification based on S deposition (wet and dry)

Class	Deposition (gm^{-2})
1	< 2.46
2	$2.46 \leq 3.33$
3	$3.33 \leq 3.74$
4	> 3.74

Last we stratified the NE data based on atmospheric deposition of wet and dry S. S was chosen because it is a major component of acidic deposition (NAS, 1984). The wet S deposition used is discussed in Wampler and Olsen (1987) and dry S deposition was obtained from simulations using the Regional Acid Deposition Model (RADM, R. Dennis and S. Seilkop, unpubl. data; T. Clark and S. Seilkop unpubl. data). In these analyses we used a simple stratification procedure based on the distribution of the S deposition for our study sites. We defined four classes based on the 25 and 75th percentiles and the median value of the deposition data (Table 3).

Statistics

We used several statistical techniques to explore potential relationships between mapped parameters and surface water chemistry. We performed stepwise regressions (SAS, 1985) on the continuous independent variables, using Mallows's C_p as a model selection criterion. We used scatter plots to look for qualitative relationships, and we used residual plots to check our regression assumptions. Furthermore, we excluded outliers and points of influence. Outliers were identified as points with studentized residuals greater than 3.3 in absolute value. The value of 3.3 was chosen ad hoc, so that residuals outside of 3.3 standard deviations from the mean would be excluded, but realistic values of a large number of observations from a normal distribution would not be truncated. Potential influential points were identified using Cook's D (Belsley et al., 1980), and the points were excluded if they had a large effect on the parameter estimates according to the calculated DFBETA's (Belsley, Kuh and Welsch, 1980). When categorical variables (e.g., stream order) were found to make a significant contribution, the final model analyses used analysis of covariance.

These statistical analyses are exploratory in nature, and should not be construed as providing exact predictive relations between surface water chemistry and hydrologic/geomorphic parameters. It is unrealistic to consider these relationships to be strictly linear. For this reason, we have chosen to fill in the tables with + or - to indicate the direction of significant relationships, rather than a possibly misleading estimate of slope.

RESULTS AND DISCUSSION

For our 144 study watersheds in the northeastern United States, we determined 31 geomorphic/hydrologic parameters (Table 1). These are a combination of both direct map measurements and parameters calculated from map measurements. Also, we did a survey of the 144 lakes using 7.5 minute maps, aerial photography and field reconnaissance to identify potential seepage lake systems. Three watersheds were identified as re-charge seepage systems based on an approach discussed by Baker et al. (1990). These systems contained low SiO_2 (Linthurst et al., 1986) and were surrounded by sandy soils (Lee et al., 1989). Due to probable differences in hydrologic response of re-charge systems versus the other watersheds, we dropped these three watersheds from the analysis. We also identified two systems as having mining activity that resulted in unusually high sulfate concentrations. These two watersheds were excluded from analyses that involved lake sulfate concentration.

Northeast regional analyses

Examination of bivariate scatter plots for possible relationships identified no obvious relationship between surface water chemistry parameters and the geomorphic data. There did appear to be a trend, however, in ANC relative to stream order. Low ANC values tended to be associated with lower order watersheds and higher ANC's are associated with higher order watersheds. The trends associated with stream order might be linked to other variables, such as atmospheric deposition or watershed elevation. In general, the lower stream order systems were concentrated in the higher elevation areas where S deposition tends to be high.

Using stepwise regression we identified significant relationships between surface water chemistry and hydrologic/geomorphic parameters for total Al, ANC, DOC, SO_4 , pH and SBC (Table 4). We were only able, however, to describe a limited amount of the variance ($R^2 = 0.11-0.30$). Runoff tended to be the most consistent predictor, being negatively related to ANC, SO_4 , pH and SBC, and positively related to total Al. The negative correlation to runoff might be due to dilution effects. The positive relationship with Al might be due to increased total Al in solution given that decreasing pH and ANC would be linked with more acidic surface water conditions (Cronan and Schofield, 1979; Johnson et al., 1981).

Stream order was also identified as an apparent important classification variable. Systems with low pH, ANC and DOC values and high SO_4 values tended to be associated with first and second order watersheds. These watersheds tended to be headwater systems that were generally composed of high elevation lakes with small drainage areas that could result in a higher potential for quick flow runoff and associated reduced potential for neutralization of acidic inputs. The low DOC values would also be expected from systems that were dominated by quick runoff.

TABLE 4

Results of stepwise regression relating surface water chemistry vs. geomorphic/hydrologic parameters for the whole NE ($n = 141$)

	Al*	ANC	COLOR	DOC	SBC	SO ₄	pH
B-LEN							
COMPACT							
DDENSITY		+					+
ELEV	+						
H ₂ O-WS			-	-			
MAXREL				-		-	+
PERIN		-					
RT				-			
RUNOFF	+	-			-	-	
STRMORDER		+		+		-	+
Total R ²	0.30	0.15	0.17	0.21	0.11	0.29	0.20

* Al, ANC, SBC and pH: $n = 141$; SO₄, Color: $n = 139$; DOC: $n = 140$.

The limited amount of explained variance in these exploratory stepwise regressions might have been due to heterogeneity in the data across the NE. Also, influence of other factors such as soils, geology, or deposition might be affecting the total regional findings. Stratification into smaller regions that help account for the influence of these factors might improve the relationships. Therefore, we conducted stepwise regression analyses examining smaller more homogeneous sub-regions within the NE based on deposition, geography/geomorphology and statistical classifications.

Stratification analyses

MLRA

We identified noticeably improved relationships ($R^2 = 0.28-0.59$; Table 5) between the geomorphic/hydrologic parameters and surface water chemistry for region R143 compared to the NE overall. Region R143 encompasses high elevation areas of New England and New York (Fig. 2a). Elevation and runoff were the most consistent predictors; elevation being positively correlated with total Al and SO₄, and negatively related with ANC, pH and DOC. Acidic deposition of S is generally higher in high elevation regions in the NE (i.e., Adirondacks, see Olsen and Slavich, 1986). The high deposition could lead to lower ANC and pH values in the high elevation areas. The lowered pH is probably strongly interrelated to Al and elevation. Decreased pH results in higher concentrations of Al in solution. Past work by Cronan and Schofield (1979), Johnson et al. (1981) and Hooper and Shoemaker (1985) indicates a strong correlation between increasing Al and decreasing pH. Also, the

increased total Al might influence the negative DOC relationship due to formation and precipitation of alumino-organic complexes.

Stream order, as a classification variable, was negatively correlated with SO_4 , indicating that lower stream order systems tend to be related to high SO_4 concentrations. The findings support those discussed for the whole NE studies.

We observed significant relationships in two other MLRA regions: R144A and R144B. These two regions are defined as New England and Eastern New York uplands, southern and northern parts, respectively (USDA, 1981). Several

TABLE 5

Summary of stepwise regression results for surface water chemistry and geomorphic/hydrologic parameters based on Major Lane Resource Associations (MLRA)

	Al	ANC	COLVAL	DOC	SBC	pH	SO_4	SiO_2
<i>R143, n = 59</i>								
B-LEN		+						
B-PERIM					+			
B-SHAPE	+				+			
ELEV	+	-		-		-	+	
$\text{H}_2\text{O-WS}$			-	-			+	
MAXREL						+		
MEANPATH		+						
REL-RAT			-					
RUNOFF	+	-		-	-	-		
WTPATH					-			
Total R^2	0.40	0.50	0.34	0.28	0.57	0.51	0.43	
<i>R144a, n = 27</i>								
B-WIDTH								+
DDENSITY								+
ELEV	+							
MAXREL								-
MEANPATH					+			
PERIMRAT		+						
REL-RAT			+	+				+
RT			-	-				
RUNOFF	-							
Total R^2	0.27	0.16	0.35	0.31	0.15			0.46
<i>R144b, n = 34</i>								
ELEV			-	-			+	
$\text{H}_2\text{O-WS}$			-					
INTERMIT			-					
MAXREL	-							
MEANPATH			+					
PERIMRAT				+				
PERIN	+							
WS-LA	+							
Total R^2	0.57		0.51	0.35			0.44	

characteristics were included as significant predictors for water chemistry parameters for R144A ($R^2 = 0.16-0.46$; Table 5). Relief ratio was the most consistent predictor, with positive relationships observed for Color, DOC and SiO_2 . Relief ratio is often used as an indicator of general watershed slope with a high ratio indicating greater watershed slope. We would expect high relief ratio systems to have greater portions of quick runoff, thus resulting in lower observed values of such parameters as DOC and color. For R144A, however, elevations are fairly low and relief in general is gentle. In this instance we suspect that relief ratio might be a surrogate for some other parameter not apparent in this analysis.

MLRA region R144B also had several parameters indicated as significant predictors of chemistry ($R^2 = 0.35-0.57$; Table 5). We observed elevation as the most consistent predictor, being negatively related with Color and DOC and positively related with SO_4 . The positive relation with SO_4 may reflect elevational relationships with atmospheric S deposition, with high S deposition occurring in some higher elevation areas of the NE (Olsen and Slavich, 1986). Also, high elevation areas tend to have quicker runoff due to increased slopes. The positive relationship with elevation in R144B supports the patterns observed in MLRA R143.

Hammond's regions

We also found significant relationships (Table 6) for the Hammonds regions B4 and C5 (Fig. 2b). Although, these regions are very similar to MLRA regions R144B and R143, their delineation is based more strongly on geomorphic and topographic features. Region B4 is characterized by upland areas with moderate slopes. We were able to explain a significant portion of the variability for total Al, Color, SiO_2 and pH ($R^2 = 0.61-0.69$; Table 5). Also, we determined significant relationships for ANC and SBC. The most consistent predictor was elevation with total Al being positively related and ANC and pH being negatively related. The elevational relationship with these parameters is consistent with those discussed earlier for the MLRA regions.

Hammond's region C5 is composed mainly of high elevation areas with steep side slopes. We identified significant correlations for Al, ANC, Color, DOC, SiO_2 and SO_4 ($R^2 = 0.16-0.35$; Table 6). The relationships in C5 tend to be quite a bit lower than in B4. Elevation once again was a consistent predictor of surface water chemistry. ANC, Color and SiO_2 were negatively related with elevation and total Al and SO_4 were positively related. These findings are similar to those reported above, indicating that elevation in northeastern hill and mountain country is an important consideration for surface water chemistry. We also identified a significant positive relationship between watershed-to-lake-area ratio and ANC, Color and SiO_2 for region C5. In these higher elevation areas a high watershed-to-lake-area ratio probably indicates a moderately sloped watershed where runoff rate and lake flushing are somewhat slowed. The reduced runoff rate might aid in neutralization of incoming acidic inputs resulting in a higher ANC and SiO_2 . Gentler slopes are often associated

TABLE 6

Stepwise regression results for surface water chemistry and geomorphic/hydrologic parameters based on physiographic land surface forms

	Al	ANC	COLVAL	DOC	SBC	SiO ₂	pH	SO ₄
<i>B4, n = 30</i>								
B-SHAPE					+			
DDENSITY							+	
ELEV	+	-					-	
ELONG	-							
INTERMIT			-					
MEANPATH			+			-		
PERIMRAT			+					
PERIN						+		
REL-RAT								
WS-LA	+					+		
Total R ²	0.69	0.21	0.67		0.23	0.67	0.61	
<i>C5, n = 53</i>								
ELEV	+	-	-	-				+
INTERMIT			-			-		
OPENAREA						-		
RT			-	-				
RUNOFF			+	+				-
WS-LA		+	+			+		
Total R ²	0.25	0.16	0.35	0.19		0.45		0.35

with wetland and lower flushing rates. In this region this probably accounts for the positive relationship with Color.

Statistical clusters

The statistical clustering resulted in three classes that had significant relationships between surface water chemistry and geomorphic/hydrologic parameters. These include: (1) Class 1 made up of low stream order, low relief systems, (2) Class 3 composed of systems with stream orders of 3 and medium elevation and relief and (3) Class 5 which is made up of high relief, high-elevation systems with stream orders of 0, 1 or 2 (Tables 2 and 3).

For the Class 1 systems (low order, low elevation, $n = 27$) we identified significant relationships for ANC, Color, DOC, SiO₂, SO₄ and pH ($R^2 = 0.11-0.62$; Table 7). We identified significant relationships for total Al, ANC, Color, DOC, SBC, SiO₂, SO₄ and pH ($R^2 = 0.12-0.62$; Table 7) for the Class 3 systems (medium elevation, high stream order). Class 5 systems (low stream order, steep relief and elevation) significant relationships were identified for ANC, Color, SiO₂, SO₄, pH and SBC ($R^2 = 0.20-0.49$). In general the relationships identified for the three statistical clusters were stronger than for the entire NE region.

They were not, however, as consistently improved as were the results of the MLRA and Hammond's analyses. By classifying on elevation, stream order and relief ratio we are probably reducing some of the overall explanatory power of the hydrologic/geomorphic data, inasmuch as these three parameters (particularly elevation and stream order) have been identified earlier as significant factors explaining surface water chemistry. The result is probably the reduced consistent improvement in explaining surface water chemistry relative to what we observed using MLRA and Hammond's.

We also ran a one way AOV, with Tukey's methods for comparing means to determine if significant differences in surface water chemistry existed among the three classes (Classes = 1, 2 and 3). We found some differences among the classes. The results, however, were not consistent. The major chemistry variables that were significantly different among the classes were SBC, ANC and total Al. Although, the overall results of the statistical clustering indicates that the variables we chose to group on aided in explaining some variability in the surface water chemistry there is still significant noise in the data. The noise is probably due to the previously discussed factors: soils, geology and deposition. Also, indications are that the groupings we identified represent some distinct regions that possibly vary hydrologically and thus have some differences in chemistry due to hydrologic response.

Sulfur deposition

We stratified the NE watersheds based on total S deposition (Table 3) and used stepwise regression to test for relationships among the geomorphic/hydrologic parameters and surface water chemistry by deposition class. Also, we used an AOV test, to identify if there were significant differences in average chemistry among the four deposition classes.

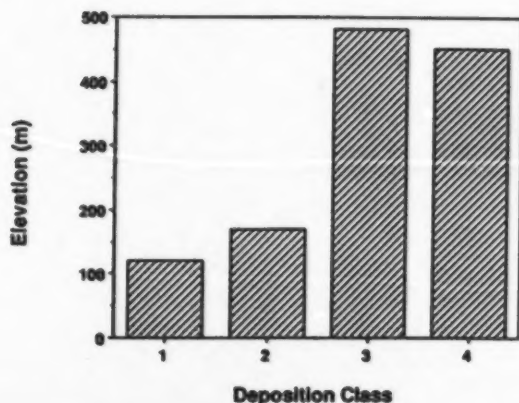


Fig. 3. Median watershed elevation by S deposition class.

TABLE 7

Stepwise regression results for surface water chemistry and geomorphic/hydrologic parameters based on S deposition stratification

	Al	ANC	COLOR	DOC	pH	SBC	SiO ₂	SO ₄
<i>Depcls = 1</i>								
COMPACT					+			
DDENSITY		+			+	+		
ELEV							+	
H ₂ O-WS	-		-					+
INTERMIT				-				
MAXREL								+
PERIMRAT		-		+				
PER-DD		+				-	+	
REL-RAT				-				
RT				-		-		-
RUNOFF		-			-	-		-
STRORDER	-							
WS-LA								
Total R ²	0.22	0.55	0.27	0.47	0.42	0.59	0.62	0.39
<i>Depcls = 2</i>								
B-PERIM		+						
B-WIDTH		+						
COMPACT						+		
ELEV							+	
H ₂ O-WS			-	-				
MAXREL		+				+		
PERIMRAT							+	
REL-RAT			-					
STRORDER						-		
WSAREA		-						
Total R ²		0.47	0.34	0.31		0.33	0.43	
<i>Depcls = 3</i>								
B-SHAPE	+							
ELEV	+							
DDENSITY		+			-	-		
H ₂ O-WS		-				-		
INTERMIT							+	
MEANPATH					-			
PER-DD		-						
ROTUND	-							
VOL	-	+				+		
WSAREA					+	+		
WS-LA							+	
Total R ²	0.69	0.72			0.37	0.76	0.24	
<i>Depcls = 4</i>								
B-PERIM								
COMPACT		-						
ELEV		-						-
ELONG		-		+			+	
H ₂ O-WS			-	-			-	
MAXREL			-					
PERIMAT			-					
REL-RAT								-
RUNOFF		-						-
Total R ²		0.44	0.55	0.49			0.49	0.42

Results of the AOV analysis indicate that there are significant differences in surface water chemistry relative to deposition class. We found that concentrations of total Al and SO_4 were significantly higher on the average for the watersheds in the higher Deposition Classes 3 and 4 (i.e., higher deposition watersheds, Table 3) and that ANC and SBC were significantly lower for those systems. We also found significant differences in watershed elevation with Classes 3 and 4 dominated by higher elevation systems (Fig. 3). These results indicate that S deposition is related to elevation and that the high elevation systems tend to be low ANC systems.

Table 7 summarizes the results of the stepwise regression analysis. In general stratifying on S deposition improved relationships between chemistry and the geomorphic/hydrologic parameters. In Deposition Class 1 we found that drainage density, the ratio of surface water area to watershed area, and runoff were the three most consistent predictors of surface water chemistry. In the higher Deposition Classes, elevation, basin shape parameters and watershed area were consistent predictors of chemistry. As discussed above there is a strong relationship between elevation and deposition. Also, indications are that surface water chemistry is strongly related to deposition. The inclusion of the basin shape parameters and watershed area as important predictors in these regions indicates that the length of the potential flowpath of runoff is important in the higher deposition areas. The longer flowpath increases the potential for neutralization of acidic deposition. Also, larger watersheds are likely to have deeper soils near the lake depending on local topography.

In summary, the results of the analyses based on deposition stratification indicate that a significant amount of surface water chemistry can be explained by geomorphic and hydrologic factors. It is important, however, to consider these factors in close conjunction with atmospheric deposition particularly when looking at chemistry variables that are influenced by acidic deposition of S such as ANC, pH, SO_4 , total Al and SBC.

CONCLUSIONS

We tested relationships among mapped geomorphic/hydrologic parameters and surface water chemistry (total Al, ANC, Color, DOC, SO_4 , pH, SiO_2 , and SBC) for 144 watersheds located in the NE. We found that stream order was the most consistent significant predictor of surface water chemistry on a regional scale. Stream order was negatively related with SO_4 and positively related with ANC and pH. Other factors that were included as significant predictors include maximum relief, runoff and elevation. In all cases the amount of variability explained by these parameters on a regional scale is significant but small.

Looking at relationships between surface water chemistry and the watershed parameters on a subregional scale improved the overall relationships for specific regions. The strongest relationships were identified in the high elevation areas of the NE (Adirondack Mountains). In the subregional

analysis, elevation and stream order were the most consistent predictors. The relationship between stream order and chemistry on the subregional scale was the same as for the entire region. Elevation tended to be positively correlated with SO₄ and negatively correlated with ANC and pH. Additionally, we found that elevation was related to deposition based on the defined depositional classes. This finding supports previous work by Schofield (1976) and Hunsaker et al. (1986) indicating that elevation was an important predictor of surface water chemistry in the Adirondacks.

The correlation analysis based on statistical clustering yielded limited significant relationships among the watershed parameters and surface water chemistry. Based on the cluster analysis, we identified two physiographically distinct regions in the NE based on the watershed parameters; the high elevation Adirondack area and the coastal areas of Maine and Massachusetts.

We feel that an important finding of this study is that significant relationships exist between annual values of surface water chemistry and geomorphic/hydrologic parameters, even on a regional scale. Watershed characteristics affect hydrologic response and, thus, indirectly affect surface water chemistry on relatively short time scales (Johnson et al., 1981). This study indicates that those effects are observable on longer time scales.

We think that the results of the stratified data analysis strongly support the importance of hydrology in determining surface water chemistry. By removing some of the variability in the chemistry data due to the factors discussed above we found significant improvement in the amount of variability explained by the geomorphic/hydrologic parameters. The improved relationships between the hydrologic/geomorphic parameters and surface water chemistry for the subregions delineated based on deposition, soils geography and geomorphology indicate the importance of these factors to the chemistry of surface water. Also, it is apparent that the effects of hydrology on surface water chemistry are closely linked to these factors. This analysis is a first step towards integrating these additional factors into a descriptive statistical model that explains surface water chemistry.

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